

LIMITING TEMPERATURES IN MULTIFRAGMENTATION

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Abstract

The systematic data set on isotopic effects in spectator fragmentation collected recently at the GSI laboratory permits the investigation of the N/Z dependence of the nuclear caloric curve which is of interest in several respects. In particular, new light is shed on the proposed interpretation of chemical breakup temperatures as a manifestation of the limiting temperatures predicted by the Hartree-Fock model. The obtained results are discussed within the general context of temperature measurements in multifragmentation reactions.

1 Introduction

Limiting temperatures are a manifestation of the fragility of nuclear fragments in the hot environment generated during energetic reactions. If the level of energy transfers exceeds a given limit the produced nuclei will not survive as bound objects but rather disintegrate into smaller entities, nucleons, complex particles, or very small fragments. On the other hand, for observing fragmentation, it is necessary to provide substantial amounts of energy in order to overcome the binding forces causing the resilience of nuclear systems against fragment formation [1, 2]. The limit up to which compound nuclei can exist will have to be exceeded. Multifragmentation reactions are thus characterized by a delicate energy balance.

The decay channels available for excited nuclei have been studied by Gross et al. within a phase space model [3]. Following the principles of Weisskopf theory for evaporation they calculated the asymptotic phase space available for the system. The main assumptions in this particular model were an expanded volume in order to accommodate the fragments, particle emissions faster than the reaction time so that only gamma decaying states had to be considered, and equal a priori probabilities for the accessible states. The many decay channels obtained from microcanonical sampling were sorted into the classes of evaporation, fission, cracking, and vaporization. Cracking here denotes the appearance of at least three substantial fragments while vaporization indicates the complete disintegration into nucleons and light fragments with mass numbers $A < 20$. It was found that cracking is the dominant reaction channel for the studied ^{238}U nuclei at excitation energies of the order of 1 GeV (Fig. 1). Cracking diminishes quickly at smaller and higher excitation energies which reflects the above mentioned limits. The resulting rise and fall of fragment production predicted by this and other, similar, models [4] was found to be in good agreement with the experiment [5, 6].

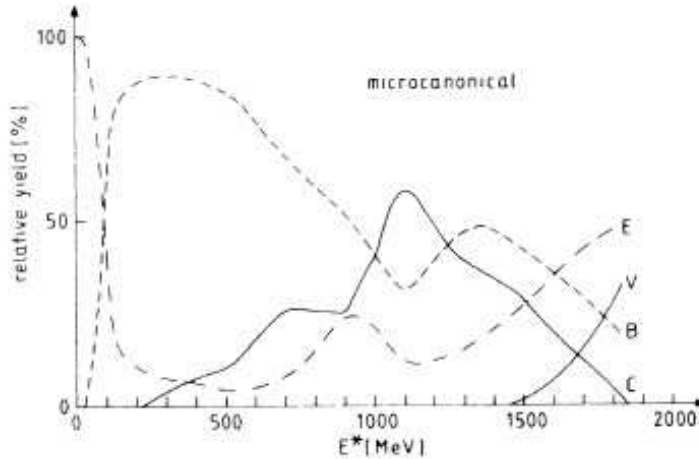


Figure 1: Relative strength of the decay channels of ^{238}U nuclei excited to energies up to 1800 MeV. A distinction is made between evaporation labelled E, binary decay channels (B, pseudo-fission), cracking (C, three or more fragments with $A \geq 20$), and vaporization (V, only fragments with $A < 20$). The lines give the results of a microcanonical Monte Carlo calculation (from Ref. [3]).

2 Limiting temperatures

The temperatures to be exceeded for observing this new class of reaction processes have received special interest also for their connection with the nuclear equation of state. Calculations suggested a nearly linear relationship between the limiting temperatures at which compound nuclei can still exist and the critical temperature of nuclear matter [7-10]. Quantitative experimental results for the former would thus serve as a valuable source of information on nuclear matter properties.

The stability of hot compound nuclei has been studied within the temperature dependent Hartree-Fock model by several groups. The problem of accounting for the continuum components of the compound-nuclear levels has been addressed by Bonche et al. [8] by considering the nucleus in thermal equilibrium with its surrounding vapor. As an example, the solution obtained for a ^{208}Pb nucleus excited to 7 MeV temperature is shown in Fig. 2. At temperatures exceeding this value, a self-bound solution is no longer found and the nuclear matter is pressed against the boundaries of the confining volume of the calculation. As evident from the figure, these calculations are restricted to homogeneous matter distributions and spherical symmetry by the choice of the trial wave functions and do not explore the partition space available for fragmentation channels. The radii remain close to their ground-state values.

A particular role in these calculations is played by the Coulomb force which if included drastically lowers the temperature limits. This is best visualized in the results of Besprosvany and Levit [11] who calculated limiting temperatures for a wide variety of nuclei within a liquid-drop approximation to the Hartree-Fock theory (Fig. 3). Along the valley of stability, with decreasing mass, the effect of the decreasing Z dominates over that of the increasing Z/A which permits excitations to

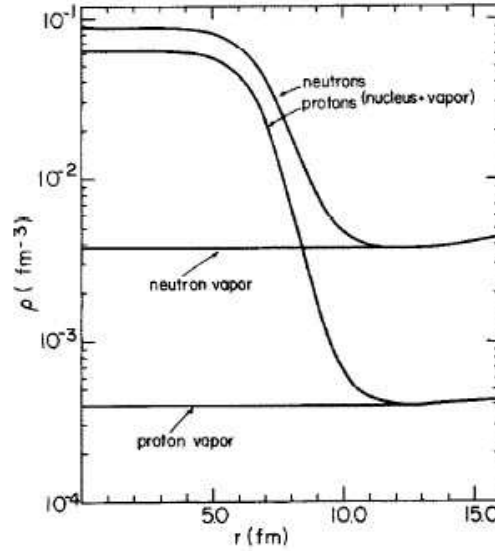


Figure 2: Radial dependence of the neutron and proton densities of nucleus+vapor and vapor solutions of the thermal Hartree-Fock equations for the uncharged ^{208}Pb nucleus at 7 MeV temperature and with the SKM interaction in a confining spherical box with radius $R = 16$ fm (from Ref. [8]).

higher temperatures before the system becomes unbound. For the same reason, the limiting temperatures vary along chains of isotopes or isobars. On the proton rich side, beyond the valley of stability, they are predicted to decrease rather rapidly. These variations with mass and isospin can serve as characteristic signatures of limiting-temperature effects in experimental data.

3 Temperature Measurements

A model-free access to the temperatures governing multifragmentation reactions is obtained by measuring, e.g., excited-state populations whose interpretation relies only on the validity of Boltzmann statistics [12]. Particle-unstable resonances in light nuclei were found to be particularly suited for this purpose because of their stability against side-feeding effects during later reaction stages. The peak structures are identified with the technique of correlation functions, and background corrections are based on measurements for resonance-free pairs of light fragments.

An example of internal temperatures measured for the fragmentation of projectile spectators from ^{197}Au on ^{197}Au reactions at 1000 MeV per nucleon is given in Fig. 4. The open symbols represent the temperatures deduced from the ratios of state populations in ^4He and ^5Li . They remain at a mean value of ≈ 5 MeV, virtually independent of the variable Z_{bound} used for the event sorting according to impact parameter.

More recently, the measurement of internal fragment temperatures has been extended to correlations between fragments and light particles [14, 15]. The emerging picture is overall very consistent. For the reaction ^{124}Xe on Sn at 50 MeV per nu-

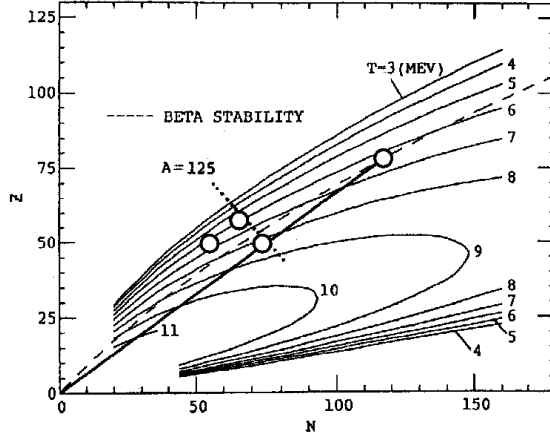


Figure 3: Location of the four projectiles used in S254 in the plane of atomic number Z versus neutron number N . The contour lines represent the limiting temperatures according to Ref. [11], the dashed line gives the valley of stability, the full line corresponds to the $N/Z = 1.49$ of ^{197}Au , and the dotted line marks $A = 125$.

cleon, the excitation energies of fragments over a wide range of Z have been found to saturate at $E/A \approx 3$ MeV which corresponds to very similar temperatures near $T = 5$ MeV. These experimental methods probe the excitation of the fragments when they are sufficiently separated from the rest of the system, so that the correlations of the decay products are not disturbed by further collisions. It is, therefore, a question whether they represent the static limit beyond which nuclei become unstable or rather a temporary property in a dynamical situation. A qualitative understanding can be obtained from the time scales of evaporation processes. Temperatures between 4 and 6 MeV correspond very generally to nuclear life times of the order of 50 to 200 fm/c [16, 17] which cover the range of time scales deduced for fragmentation reactions.

Access to earlier reaction stages is obtained from the isotope temperatures reflecting the chemical freeze-out stage of the reaction. They are deduced from double ratios of yields of neighboring isotopes, as described previously [18, 19]. In the example of the ^{197}Au on ^{197}Au reaction shown in Fig. 4, the isotope temperature T_{HeLi} rises up to about 12 MeV with decreasing Z_{bound} . Its deviation from the internal temperatures starts approximately where the drop of Z_{max} with respect to Z_{bound} indicates the transition from the evaporation to the cracking mode of decay (Fig. 4, bottom panel). The reaction events with higher temperatures, at the smaller Z_{bound} , are from sources with smaller mass, in accordance with the geometrical participant-spectator scenario. This implicit mass dependence has been interpreted by Natowitz et al. [20] as suggesting that the measured isotope temperatures may reflect the limiting temperatures of compound nuclei for which a similar mass dependence is expected.

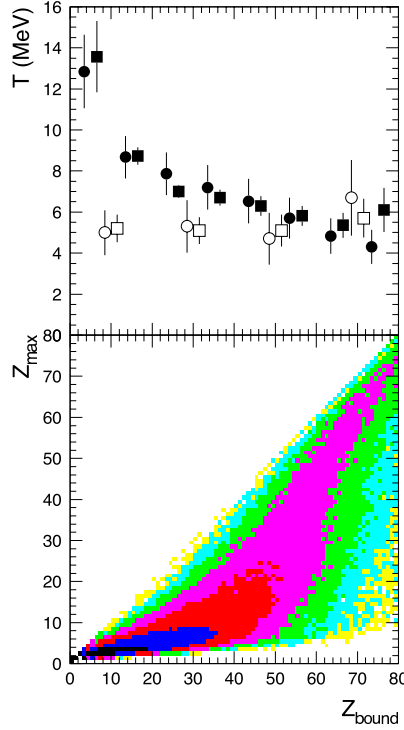


Figure 4: Results obtained for ${}^{197}\text{Au}$ on ${}^{197}\text{Au}$ at $E/A = 1000$ MeV: Top: Measured isotope temperature T_{HeLi} (full circles and squares representing the data for the target and projectile decays, respectively) and excited-state temperatures (open circles and squares representing the data for ${}^5\text{Li}$ and ${}^4\text{He}$, respectively) as a function of Z_{bound} . Average values for 10 or 20 unit intervals of Z_{bound} are given. For clarity, the data symbols are slightly displaced horizontally. The indicated uncertainties are mainly of systematic origin. Bottom: Distribution of Z_{max} versus Z_{bound} after conventional fission events have been removed. The shadings follow a logarithmic scale (from Ref. [13]).

4 ALADIN Experiment S254

The ALADIN experiment S254, conducted in 2003 at the SIS heavy-ion synchrotron, was designed to study isotopic effects in projectile fragmentation at relativistic energies. Besides stable ${}^{124}\text{Sn}$ and ${}^{197}\text{Au}$ beams, neutron-poor secondary Sn and La beams were used in order to extend the range of isotopic compositions beyond that available with stable beams alone (cf. Fig. 3). The radioactive secondary beams were produced at the fragment separator FRS [21] by the fragmentation of primary ${}^{142}\text{Nd}$ projectiles of about 900 MeV/nucleon in a thick beryllium target. The FRS was set to select ${}^{124}\text{La}$ and, in a second part of the experiment, also ${}^{107}\text{Sn}$ projectiles which were then delivered to the ALADIN setup. All beams had a laboratory energy of 600 MeV/nucleon and were directed onto reaction targets consisting of ${}^{\text{nat}}\text{Sn}$ (or ${}^{197}\text{Au}$ for the case of ${}^{197}\text{Au}$ fragmentation). The acceptance of the ALADIN forward spectrometer, at this energy, is about 90% for projectile fragments with $Z = 3$, increases with Z and exceeds 95% for $Z = 6$ and heavier fragments [6].

In order to reach the necessary beam intensity of about 1000 particles/s with the

smallest possible mass-to-charge ratio A/Z , it was found necessary to accept a distribution of neighboring nuclides together with the requested ^{124}La or ^{107}Sn isotopes. While the mass and charge of each projectile can be known from measurements with upstream detectors [22], only results obtained with the full distributions will be presented here. Their mean compositions were $\langle Z \rangle = 56.8$ (49.7) and $\langle A/Z \rangle = 2.19$ (2.16) for the nominal ^{124}La (^{107}Sn) beams, respectively. Model studies consistently predict that the same $\langle A/Z \rangle$ values are also representative for the spectator systems emerging after the initial cascade stage of the reaction. In particular, the differences between the neutron-rich and neutron-poor cases are expected to remain the same within a few percent [23, 24].

5 N/Z dependence of the caloric curve

The mass resolution obtained for projectile fragments entering into the acceptance of the ALADIN spectrometer is about 3% for fragments with $Z \leq 3$ and decreases to 1.5% for $Z \geq 6$ (standard deviations). Masses are thus individually resolved for fragments with atomic number $Z \leq 10$ [25]. The elements are resolved over the full range of atomic numbers up to the projectile Z with a resolution of $\Delta Z \leq 0.2$ obtained with the TP-MUSIC IV detector [26].

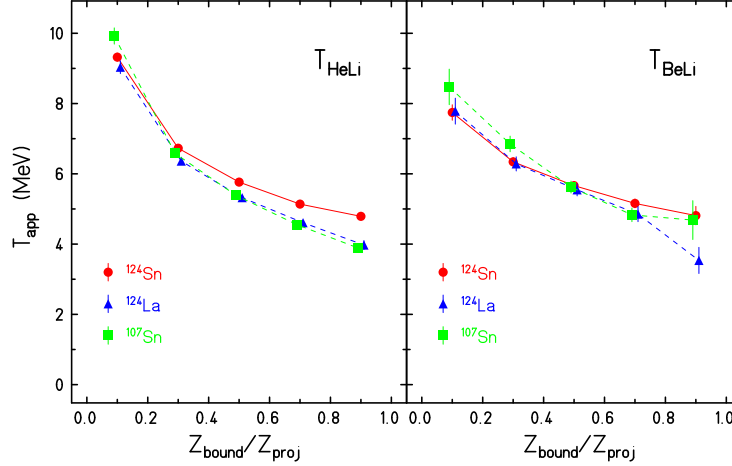


Figure 5: Apparent temperatures T_{HeLi} (left panel) and T_{BeLi} (right panel) as a function of Z_{bound} for the three reaction systems produced with $^{107,124}\text{Sn}$ and ^{124}La projectiles. Only statistical errors are displayed.

Two examples of double-isotope temperatures deduced from the measured isotope yields are shown in Fig. 5 as a function of Z_{bound} . Besides the frequently used T_{HeLi} (left panel), determined from $^3,^4\text{He}$ and $^6,^7\text{Li}$ yields also the results for T_{BeLi} are displayed (right panel). For T_{BeLi} the isotope pairs of $^7,^9\text{Be}$ and $^6,^8\text{Li}$ are used which each differ by two neutrons. The double difference of their binding energies amounts to 11.3 MeV and is nearly as large as the 13.3 MeV in the T_{HeLi} case. The apparent temperatures are displayed, i.e. no corrections for secondary decays feeding the ground states of these nuclei are applied.

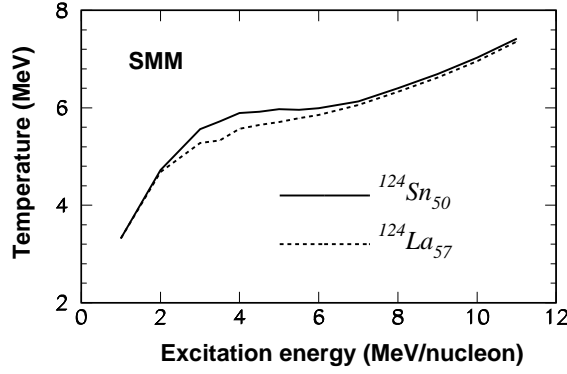


Figure 6: Caloric curves for ^{124}Sn ($Z = 50$) and ^{124}La ($Z = 57$) as calculated with the Statistical Multifragmentation Model (from Ref. [29]).

Both temperature observables show the same smooth rise with increasing centrality that was observed earlier in the study of ^{197}Au fragmentations (Fig. 4). For T_{BeLi} , the statistical uncertainties are larger in the two extreme bins at large and small Z_{bound} in which intermediate-mass fragments are not abundantly produced. T_{HeLi} , on the other hand, which mainly reflects the behavior of the $^3\text{He}/^4\text{He}$ yield ratio [13] reaches to somewhat higher temperatures at small Z_{bound} . The dependence on the isotopic composition is very small and virtually non-existent in the fragmentation channels. At the larger Z_{bound} , for which residue production dominates, the temperatures of ^{124}Sn decays are slightly larger than those of the neutron-poor systems. This tendency is more pronounced in T_{HeLi} than in T_{BeLi} .

For a quantitative comparison with the Hartree-Fock predictions, the region of transition from residue production to multifragmentation ($Z_{\text{bound}}/Z_{\text{proj}} \approx 0.7$) seems best suited. The residue channels associated with the highest temperatures are found here, resulting from the decay of spectator systems with about 75% of the projectile mass [18]. Their limiting temperatures of 9.2 MeV and 7.9 MeV for the neutron-rich and neutron-poor cases, respectively, are higher than those of the nominal nuclei while their difference is somewhat smaller (Fig. 3). The experimental mean values of T_{HeLi} and T_{BeLi} , after applying a 20% side-feeding correction [13, 18], are 6.2 MeV for ^{124}Sn and 5.7 MeV for the neutron-poor systems.

The large difference in absolute magnitude between the Hartree-Fock limiting temperatures and the side-feeding corrected double-isotope temperatures are not as crucial as it may appear at first sight. As noted already by Natowitz et al. [20], the predictions depend sensitively on the type of Skyrme force used in the calculations [9, 10]. A linear rescaling with a factor 0.71, approximately corresponding to the results obtained by Song and Su with the SkM* force [9] leads to the overall best agreement in absolute magnitude. The corresponding critical temperature for infinite nuclear matter is $T_c = 15$ MeV. However, even on the reduced scale, the predicted N/Z dependence, $\Delta T \approx 0.9$ MeV for the studied systems, is considerably larger than the experimental value. Furthermore, the interpretation of the Z_{bound} dependence as being caused by the mass dependence [20] would require that the temperature difference remains on a similar level for the full range of $Z_{\text{bound}}/Z_{\text{proj}} < 0.7$ which is clearly not observed.

A much reduced role for Coulomb effects is predicted by models which include expansion [27] or which allow the partitioning of the system. As noted long ago by Barz et al. [28], the limiting temperatures emerging from the Hartree-Fock approach are systematically too high because they are not going beyond the mean-field approximation and the formation of clusters in the excited medium is not considered. The Coulomb forces act with reduced strength in the expanded volume and are partly compensated by the nuclear forces within the formed fragments. Calculations performed more recently [29] with the Statistical Multifragmentation Model [4] predict much smaller differences for the breakup temperatures of neutron rich and neutron poor systems with a dependence on the excitation energy that is in excellent agreement with the experimental data (Fig. 6).

The open question that remains to be answered concerns the nature of the instability driving the system into the expanded configurations sampled in the statistical approaches. Following the statistical principles cited by Gross et al. [3], the mere opening of the asymptotic phase space will suffice, leading to a phase-space driven instability rather than the Coulomb instability appearing from the Hartree-Fock simulations. Furthermore, taking recourse to recent dynamical studies, one observes that the partitioning of the system with a loss of binding between the emerging parts may occur rather early in the collision [30, 31].

6 Summary

The temperatures limiting the existence of self-bound nuclei or nuclear fragments appear in different roles in fragmentation reactions. The limits have to be overcome to initiate the disintegration of the produced excited systems while they should not be exceeded by the fragments to be observed. A quantitative knowledge of these limits is not only of interest for the understanding of the reaction mechanisms involved but also for the more fundamental reason that they can provide information on the nuclear-matter equation-of-state. Hartree-Fock calculations predict a linear relation between the limiting temperatures of excited compound nuclei and the critical temperature limiting the liquid-gas phase transition of nuclear matter.

The proposed interpretation of breakup temperatures measured in spectator fragmentation as representing the limiting temperatures was derived from a common mass dependence. This is only partially confirmed by the new experimental data obtained from the study of isotopic effects in spectator fragmentation. The temperatures are smaller than the general level of the predictions and, in particular, their variation with N/Z is smaller than expected. From the highest temperatures observed for compound channels, a critical temperature of about 15 MeV is deduced. It should be considered as a lower limit because phase-space driven instabilities may initiate the disintegration before the static compound limit is reached. The good agreement with predictions of the Statistical Fragmentation Model supports this assumption.

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